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POINT CONTACT JOSEPHSON MIXERS AT 130 GHz*

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ABSTRACT

The properties of point contact Josephson junctions operated as mixers with an external local oscillator at 130 GHz have been studied, and the results compared with predictions of the resistively shunted junction model. It was found that the junctions output noise could be within a factor 1.5 of the model prediction based on thermal driving noise. When the coupling to the rf source was optimized, a factor two discrepancy was typical. The measured conversion efficiency agreed with the model, within the experimental uncertainty in the equivalent microwave circuit. The best coupling was achieved in full-height waveguide. The best overall performance, measured using the hot/cold source technique, was a single side band conversion efficiency of 0.30 and mixer noise temperature of 180 K (both ± 20%). The best junctions were made of Nb, with carefully prepared points. Non-ideal behavior in other junctions is ascribed to heating effects. There is some evidence that junctions whose resistance exceeds a threshold value of ∿ 60 ohms are no longer well described by the RSJ model. A discussion is given of possible improvements in performance with better junctions or improved rf matching.

I. INTRODUCTION

Josephson junctions are predicted[1,2] to function very effectively as the non-linear element in the mixer of a heterodyne receiver system with an external local oscillator (LO). A number of experiments in the mm wavelength region have been reported.[3-7] Of these, the best results were at 8.3 mm (36 GHz) where a single side-band (SSB) mixer noise temperature of 55 K was obtained with a conversion efficiency that sometimes exceeded unity.[5] The measurements, in which point contact junctions were used, were found to agree quite well with the predictions of the resistively shunted Josephson junction (RSJ) model. Impressive results have also been reported[6] in experiments at ≈ 1 mm (330 GHz), again using point contacts. The results have been interpreted as giving a SSB mixer noise temperature of 220 K, and a conversion efficiency 0.08.* However the detailed behavior of the mixer, in particular the optimum bias point, deviated considerably from the predictions of the RSJ model.

Other reported experiments[3,4,7] generally showed qualitative agreement with the RSJ model but much worse values of conversion efficiency, presumably because of poor microwave coupling, but perhaps also due to non-ideal junction behavior.

We have completed a series of measurements on a point contact mixer with a LO at 130 GHz. The purpose was to make quantitative comparison between experiments at this frequency and the predictions of the RSJ

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*We have adjusted the reported numbers to coincide with our definition of these parameters, given in detail in sections IX and X.

model, and also to identify some of the practical difficulties peculiar to high frequency receiver systems using Josephson junctions. The product of the normal resistance R and the critical current I_c for the junctions in Ref. 5, which showed good agreement with the RSJ model, was far below the theoretical[8,9] and experimental[10,11] upper limit. Good performance at higher frequencies can only be obtained with junctions which have larger RI_c values. It is not known whether the mixer parameters of such junctions are well described by the RSJ model. Indeed, calculations based on more sophisticated models[11-14] do predict significant deviations from the simple RSJ picture. We therefore regard the RSJ model as providing a convenient frame of reference to which experimental results can be compared, and will discuss our results in terms of deviations from that model. A summary of RSJ model predictions of mixer performance is found in Ref. 1.

A description of the microwave circuit and the cryostat used in our measurements is given in section II. The scheme used can easily be adapted to higher frequencies, and provides a number of advantages over many previously reported designs as to precision of results and efficiency of coupling to the mixer. The design of the mixer itself and the intermediate frequency (IF) system are discussed in sections III and IV respectively.

Our experiences in the art of making high quality point contact Josephson junctions are described in sections V-VII. Contacts using Nb, Ta, V, and Nb-Zr were tested. The shape of their static current-voltage (I-V) curves are compared to the RSJ model in section VI. It is found that as long as self-heating effects can be eliminated, the behavior of the junctions is qualitatively similar to the prediction of the RSJ model when the resistance is not too high. However when $R \gtrsim 60$ ohms, marked deviations from the model are observed. Similar comments apply to our measurements of junction output noise, discussed in section VII. Here we find that the noise can be within a factor of two of the model prediction, but can also be much greater.

In section VIII we compare the magnitude of the junction response to the LO with the prediction of the RSJ model. Although this is complicated by uncertainties in the equivalent microwave coupling circuit, some definite conclusions can be made. It is found that the observed response is not, on the average, significantly less than the theoretically predicted value.

Direct measurements of the conversion efficiency using the "hot-cold" source method are compared in section IX with the values that can be inferred from the LO coupling. A saturation mechanism was identified that can be important even for room temperature sources, and represents an important limitation in Josephson effect mixers. Finally in section X we tabulate the results for mixer noise temperature, conversion efficiency, and other relevant parameters for a number of the junctions that we studied. Our best results are a SSB mixer noise temperature of 180 K and a SSB conversion efficiency of 0.30. These compare very favorably with the best reported results in cooled Schottky diodes at 115 GHz. The prospects of further improvements in performance by means of improved junction parameters or microwave coupling are discussed in the concluding section.

II. THE RF CIRCUIT

In Fig. 1 we show a schematic of the overall microwave circuit and cryostat design. The mixer and some associated rf components were mounted in a sealed can which was immersed in a liquid He bath. The temperature of the junction could be raised above the bath temperature by passing a current through a heater mounted next to the mixer.

The LO was derived by frequency doubling the 65 GHz output from an OKI70V11A Klystron, yielding ∿ 0.5 mW at 130 GHz. All LO components used F-band (1 × 2 mm) waveguide, except for the section leading from the top of the cryostat to the sealed can. The latter consisted of 77 cm of circular brass waveguide with an I.D. of 2.46 mm. This was used to avoid the large heat load that would be contributed by ordinary silver waveguide.

In the sealed can the LO was coupled to the main line with a TRG F555-10 directional coupler with a measured coupling ratio of 9.6 dB. To assure that the coupler would work properly at liquid helium temperature, a termination whose properties at cryogenic temperatures are known was constructed for the fourth port. This consisted of a tapered wedge machined from <u>Eccosorb</u> <u>MF-110</u>, which has an attenuation constant of ≈ 1.4 dB/mm at 4.2 K.

To obtain an absolute calibration of the LO power coupled into the main line, a bolometer was constructed which could be inserted in place of the mixer. It consisted of a short length of brass circular waveguide (to achieve thermal isolation) terminated by a tapered Eccosorb absorber. A metal film heater resistor and carbon temperature monitoring resistor were glued to the absorber. With the space surrounding the bolometer evacuated, the reading of the crystal detector monitoring the LO power was measured as a function of the temperature rise in the carbon resistor. Then the LO was turned off, and a current applied to the heater resistor until the same temperature rise occured. This provided a calibration relating the crystal detector reading and LO power incident on the mixer, which we assumed was unchanged for successive runs. It avoided the necessity of testing the attenuation of components at helium temperature, and did not require an absolute power reading at room temperature. The accuracy of the above power calibration can in principle be very high. The calibration used in this work had a rather large uncertainty, ± 15%, due to the presence of drifts in temperature of the absorber which probably resulted from inadequate thermal anchoring of electrical leads. No effort at refining the measurement was made, as the quoted uncertainty was considered adequate for our purposes.

The main line of the cold directional coupler was connected via a copper transition to an 81 cm length of brass K-band (4.3 × 10.7 mm) waveguide, which was open at the top (except for a 50 μm mylar window). A well defined flux of black-body power could be channelled down this oversized waveguide, by laying a piece of Eccosorb AN-72 foam on the top. A source temperature of 77 K resulted when the Eccosorb was located at the bottom of a Styrofoam cup filled with liquid nitrogen.

The fraction of this black-body power that entered the directional coupler can be calculated as follows: The attenuation constant of brass K-band waveguide was determined to be 0.92 dB/m at room temperature by using a pair of F band - K band transitions and a long length (> 5 m) of waveguide. In back to back tests the transitions appeared to have an additional loss of 0.5 dB apiece. Most of this is probably due to mode conversion, rather than conductor losses. In our experimental setup, all the modes of the K-band waveguide are filled by the black-body source. Hence, if we can assume that the attenuation of the higher order modes is similar to that measured for the dominant one, mode conversion effects in the transition can be ignored.* Conductor losses in the transition and coupler have been estimated to be about half their values at room temperature, on the basis both of measurements of silver waveguide at 4.2 K and rough calculations based on the anomalous skin effect. These considerations lead to an estimate of 0.8 dB loss of black-body power in the transition and coupler. On the other hand, the loss in the brass K-band waveguide is taken to be the same as its room temperature value, 0.75 dB, since its resistivity is nearly independent of temperature. From these numbers we conclude that 70% of the black-body power incident at the top of the cryostat exits the coupler. In addition, power is radiated from the walls of the K-band waveguide. An estimate of the effective temperature of this radiation (referred to the output of the coupler) is $0.83(1-A)T_G = 20$ K, where A is the attenuation of the guide and an average temperature of $T_G = 150$ K is assumed. Similar arguments lead to an estimated black-body power coupled in from the LO line corresponding to a temperature of ~ 21 K (Attenuation in the line = 3.6 dB, average temperature = 150 K).

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*This point seems not to have been considered in Ref. 6, where it plays an important quantitative role.

The apparatus described here could probably be used with little modification on a radio telescope. The main addition required would be an appropriate horn at the input end of the K-band waveguide. It has the advantage of low signal loss, a low level of background (re-radiated) power, and stable, broad band rf coupling.

III. MIXER DESIGN

The mixer consisted of two brass blocks with a channel comprising the waveguide milled in one of them. A piece of superconducting foil clamped between them constituted one broad wall of the waveguide. Figure 2 shows in cross section one version of the rf matching scheme that was used. The pointed superconducting wire (diameter ∿ 0.30 mm) is mounted in a section of 1/3 height waveguide. It is plated with copper and soldered with Wood's metal in a short length of stainless steel capillary (0.51 mm diameter). The capillary is permanently epoxied in place using Stycast 2850FT. This epoxy was used because of its tolerance to the high temperatures used in soldering, and because it contains particles of filler that are about the size required to keep the capillary centered in the hole through which it enters the waveguide. The index of refraction of the Stycast at 4.2 K was measured with a Fourier transform spectrometer to be n = 2.2. The loss was small enough to be neglected. We can then estimate the characteristic impedance of the coaxial line formed by the capillary and the feedthrough hole to be $Z_o \simeq 3.4$ ohms. When the length ℓ is approximately $\lambda/4$, leakage of 130 GHz power out of the coaxial line should be negligible.

To make a point contact, the wallwas deformed slightly by rotating the 0-80 screw. The contacts thus formed were usually stable enough that their characteristics were unchanged when the mixer temperature was changed by a few degrees or the back-short was moved.

The back-short was a brass block which was a loose fit in full height waveguide. A contacting short could not be used because of microphonic coupling to the point contact. From its clearance in the waveguide we estimate a reflection coefficient $\Gamma \approx 0.9$. Had a short of similar clearance been used in reduced height waveguide, it would have been excessively lossy. The transitions to full height waveguide on either side of the point contact produced a combined reflection $<1\%$ in power.

Several variations on the mixer design described above, were also tried: (1) A three section step transformer connecting the full and reduced height sections was used instead of a tapered transformer. (2) A number of experiments were performed in full height waveguide. (3) The length ℓ of the IF filter section was designed to be $3\lambda/4$ in early versions of the mixer. (4) When wire of diameter 50 μm was used, it was first spot welded or crimped to a wire of the proper size to be soldered in the capillary.

IV. INTERMEDIATE FREQUENCY SYSTEM

The wire forming the point is connected directly to a 50 ohm coaxial line leading to the IF amplifier, and through a 10 μH inductor to the dc bias circuit. To minimize rf interference, all dc leads entered the cryostat via filters having a minimum insertion loss of 70 dB above 300 KHz. The first stage IF amplifier was connected to the solid jacketed IF line near the point where it entered the cryostat. This amplifier had a reverse isolation > 27 dB from 0 - 500 MHz. Finally, the experiments were performed in a sub-basement where rf fields from radio and TV stations are greatly attenuated.

The junction noise was measured in the vicinity of 50 MHz using a method developed in Ref. 5. The IF chain was calibrated by substituting normal metals for the contact and measuring the output power P_{IF} for several temperatures (293 K, 78 K, and 4.2 K) and for contact resistances R in the range 10 - 300 ohms. These results were fit to the expression:

$$P_{IF} = AT + B \,, \tag{1}$$

where A and B are functions of R. Calibrations of A and B were obtained both for a narrow-band IF system centered around 50 MHz and a broad-band system which responded from 5 - 400 MHz. An effective output temperature $T_{out} = (P_{IF} - B)/A$ could subsequently be determined for a Josephson junction by noting P_{IF} and the differential resistance R_D, with A and B evaluated at $R = R_D$. The uncertainty in T_{out} is estimated to be ± 2 K with this method. Note that it automatically includes the effects of IF mismatch, loss in the IF line, etc. The noise temperature of the first stage IF amplifier (Avantek UAA-1162B) is ≈ 100 K for R_D near 50 ohms.

V. JUNCTION FABRICATION

We have tested junctions made of several superconductors: Nb, Ta, V, and Nb-25% Zr alloy. The points made from 0.3 mm wire were usually sharpened on #600 sandpaper. There was no evidence that more elaborate sharpening techniques (which could produce points whose radius of curvature could barely be resolved in a light microscope) resulted in any difference in junction properties. Nor was any change observed when the points were chemically etched after being sharpened. To make points on samples of 50 μm diameter Nb wire, two techniques were used: electrolytic etching (6 mA/mm^2 current density, with an electrolyte of 1:1 HF:H_2O), and slicing on a diagonal through the wire with a sharp razor blade. The pieces of superconducting sheet comprising the flat side of the point contact were polised electrolytically or mechanically abraded with sandpaper just before assembly.

Mounting the point in the mixer required that its temperature be raised to ∿ 70°C for 10-15 minutes to melt the solder and position the wire. The cryostat could then be assembled and cooling to LN temperature began within about 30 minutes. In the case of pure Nb we find that, a delay of the order of a day after preparing the point and flat significantly degrades the properties of the junctions. On the other hand, we did not find, as other groups have reported,[11] that etching the point and flat just prior to assembly noticeably improved the junctions.

VI. JUNCTION I-V CURVES

In the theory of Josephson effect mixing the normalized frequency $\Omega = h\nu_{LO}/2eRI_c$ enters as an important parameter. To achieve the best results we should have $\Omega < 0.6$, which corresponds to $RI_c > 500\ \mu V$ at our operating frequency. We found that sufficiently high values of RI_c could be obtained in junctions made from a variety of materials (Nb, Ta, V, and Nb-25% Zr) provided the opportunity for oxidation of the contact area was minimized. Another requirement for mixers, that the I-V curves be non-hysteretic, was not so easy to realize. In many cases the I-V curves, even though single-valued, deviated considerably from the RSJ model predictions.

Our most successful junctions were made using pure Nb. The most reliable technique was to slice a 50 μm wire on a diagonal with a sharp razor blade, mechanically abrade the opposing flat with sandpaper, and cool the apparatus as rapidly as possible. An example of the I-V curves that were obtained is given in Fig. 3. It was necessary to heat this junction somewhat above 4.2 K to avoid hysteresis. The curve without rf applied has a great deal of structure which is ascribed to coupling to parasitic resonances. Its most pronounced departure from the RSJ model prediction is the initial region of low differential resistance at low voltages. We have found that this sort of structure correlates with good mixer performance. It has been seen in variable-thickness microbridges[15,16] and is ascribed to non-equilibrium effects in the bridge.[17,18]

When LO power is applied, the I-V curves are qualitatively in good agreement with the RSJ model. We note in particular the parallelism of successive curves as the LO level is raised, the absence of subharmonic structure, and a value for the differential resistance (R_D) midway between the zeroth and first steps that is quite close to theoretical.[1]

The "good" junctions generally had a differential resistance within a factor 2 of the RSJ model prediction, provided the normal resistance was not too high ($R < 60$ ohms) and the normalized frequency was less than ~ 0.4. The discrepancy in the case of high Ω is probably related to the presence of "excess current" in virtually all of our junctions. The first step occurs at a higher average current than given by the RSJ model, leading to a reduced R_D between steps. The explanation in the case of high R junctions does not appear to be so simple. For the example of a 70 ohm junction shown in Fig. 4, R_D is smaller than the model prediction by at least a factor 3. This behavior was characteristic of all the high R junctions, and may possibly be due to the decreasing size of the contact.

We found it much more difficult to obtain non-hysteretic junctions using other materials and/or point preparation techniques. Generally as the contact pressure increases the RI_c product stays approximately constant, but the amount of hysteresis increases as R decreases. This is the opposite of the trend that would be expected if hysteresis is due to shunt capacitance at the point,[19] and suggests that self-heating was important.[20,21] If P_o is a characteristic scaling power for self-heating effects, we expect the hysteresis to be governed by RI_c^2/P_o. In a recent calculation by Tinkham <u>et al</u>.[22] for the case of a metallic contact it was found that P_o depends primarily on the materials and only weakly on the detailed dimensions (and hence resistance) of the contact.

Such a dependence of P_o (as opposed to others that have been proposed[20]) will explain the trends in junction hysteresis that we observe.

The scaling power P_o can be estimated either from the onset of hysteresis, or from the maximum voltage at which steps can be observed on the I-V curve.[22] The latter procedure is more accurate since it is less sensitive to noise and to deviations from the RSJ model. In one series of junctions using Nb-25% Zr as both point and flat, the value of P_o required to account for the observed hysteresis was of the order of 75 nW and remained constant within 25% while RI_c^2 changed by a factor of 10. For the same set of junctions, the maximum voltage at which steps occurred gave a value of P_o in the range of 15 nW. By contrast, our "good" junctions made with pure Nb as described above, always showed steps out to much higher bias voltage. The inferred values of P_o were of the order of 1 μW.

In the theory of Tinkham _et al_., P_o is expected to be of the order of 10 μW for pure metals, and to depend on the resistivity ρ of dirty metals as $\rho^{-3/2}$. This can account for the low values observed in contacts using the Nb-Zr alloy, but not those found in junctions of Nb or Ta made with 0.3 mm wire. The residual resistivity of these samples at 4.2 K was less than half what it was for the 50 μm Nb wire. Possibly our technique for pointing wires of 0.3 mm diameter changed the metallic properties near the point.

When the 50 μm Nb wire was etched to a point rather than sliced, there was frequently evidence of a large value of P_o accompanied by hysteresis. Subsequent inspection revealed that the points had been considerably flattened in the course of making the contact. It is plausible that hysteresis in this case was due to capacitance. Possibly the slicing technique sufficiently work-hardens the metal near the contact to minimize flattening.

Non-hysteretic I-V curves could be obtained in junctions with a low value of P_o and low critical current. An example is shown in Fig. 5. The steadily decreasing average differential resistance between the zero'th and first steps for increasing LO levels constitutes a substantial deviation from the RSJ model prediction. Junctions of this sort tended to be excessively noisy, and thus were not very useful as mixers.

VII. JUNCTION NOISE

We have measured the output noise temperature T_{out} in our junctions using the method outlined in section IV when they are biased with a LO level where conversion efficiency is maximum i.e., with the critical current suppressed by $\sim 50\%$. A parameter β^2 can then be computed,

$$\beta^2 = \frac{T_{out}}{T} \frac{R}{R_D} , \qquad (2)$$

which is the ratio of the effective output noise current to the Johnson noise current associated with the shunt resistor R. The RSJ model simulations[1] have shown that β^2 has a simple dependence on junction parameters only when the LO is coupled through a high source impedance. With a LO level suitable for mixing, it is expected to have a broad minimum between steps whose value depends only on normalized frequency. We measured β^2 in a number of high P_o, non-hysteretic junctions whose coupling to the LO was intentionally reduced by removing the adjustable short. Figure 6 shows an example of the variation of β^2 with bias voltage. It is qualitatively similar to the predictions of the RSJ model, except that the minimum between the zero'th and first steps occurs at a voltage which is somewhat above the midpoint.

For best performance, a mixer should be biased at the first minimum in β^2. We show in Fig. 7 the measured value of β^2 at the minimum for several poorly coupled junctions. The predicted dependence on normalized frequency from the RSJ model with thermal driving noise is also shown. Note that the lower resistance junctions (filled circles) had values that were mostly within 50% of the prediction. The few samples with $R > 60$ ohms are considerably noisier (open circles), reinforcing our belief that the RSJ model does not apply to them.

We show in Fig. 8 the observed noise from high P_o junctions in various mixer configurations, whose conversion efficiency was optmized by adjusting the back-short position for maximum coupling in the LO. It is clear that the noise is somewhat worse than in the weakly coupled case, and again the discrepancy is greatest in the case of high-R junctions (open triangles). This general behavior is expected qualitatively from the simulations[1] where it was found that strong coupling to an rf source increases the output noise. Although the noise in this case depends in a detailed way on junction and coupling circuit parameters, a rough estimate of the expected values of β^2 can be made for our mixers after the coupling parameters are estimated using the methods outlined in section VIII. For most of the junctions shown, the coupling is sufficiently poor that it is not expected to contribute more than 25% additional noise. In those cases where the coupling is stronger (the junctions with the highest values of R) we indicate with an arrow the theoretical "correction" that should be used to compare the experimental results with the values of β^2 computed from the current-driven model.

In addition to an increase in noise, the simulations also predicted a pronounced dependence of the shape of the I-V curves on tuning of the rf circuit under strongly coupled conditions. Experimentally, we did not observe any such change in shape as the plunger was moved. This raises some doubt about the above interpretation of the source of excess noise.

The junctions discussed above (represented by triangles in Fig. 8) were all made with 50 μm Nb wire against a Nb flat, with the temperature $\geqslant$ 4.2 K. At lower temperatures the junctions usually became hysteretic and could not be used. The results from junctions made from other materials with generally lower values of P_o were considerably worse. The best of these (poor) results are shown as dots in Fig. 8. Most of the dots shown were for junctions made from Nb-Zr against Nb or Ta. They were selected for the best parallelism of the I-V curves, which however was never as good as in the high P_o junctions. While most of them were operated with optimized rf coupling, the correction due to finite source resistance was generally small.

It is also of interest to compare the noise in junctions without rf bias with the prediction of the RSJ model. The latter has been determined analytically[23] for regions of the I-V curve where noise rounding is not severe, and can be expressed as:

$$\beta^2 = 1 + \tfrac{1}{2}[(V/RI_c)^2 + 1]^{-1} , \qquad (3)$$

as long as eV < 2kT. The experimental results shown in Fig. 9 are quite different from Eq. (3). There are large peaks in β^2 associated with the fine structure on the I-V curve. Structure of this sort, especially the pronounced feature around 800 μV, is seen in the majority of the junctions we have made. It is probably due to resonances in the antenna impedance seen by the junction, since the voltages of the various features do not change as the junction temperature is varied. (Energy gap structure, which we also see in our junctions, will vary in position with temperature.)

If we assume that in the absence of noise these resonances would produce negative-going self-induced steps as is expected in the RSJ model,[24] it is plausible that the noise smears what would have been hysteretic regions of the I-V curve into continuous curves. A general feature of such smeared regions is excess low frequency noise.[1] Since it seems to be virtually impossible to avoid such resonances in our experimental configuration, we feel that our noise results in the absence of LO cannot be meaningfully compared with Eq. (3) or any other simple noise theory. It is interesting, however, that for the same junction with a LO bias (Fig. 6) the noise is very close to the prediction obtained from the RSJ model with thermal driving noise. Apparently when a strong external rf drive is applied the only resonance that matters is one whose frequency is close to the driving signal.

There is evidence, however, that resonances below the LO frequency can influence the shape of I-V curves of the LO-biased junctions. In Fig. 5, for example, we attribute the oscillations in R_D between the zero'th and first steps to resonances in the coaxial IF feedthrough. The feedthrough used had a nominal electrical length of $3\lambda/4$ at the LO frequency, so that a standing wave at 2/3 of the LO frequency could exist in the coaxial section. When this feedthrough was used, structure similar to that of Fig. 5 was seen in almost all junctions. When the IF feedthrough was changed to have an electrical length of $\sim \lambda/4$, the structure like that of Fig. 5 disappeared. Also, when a similar 3/4-wavelength feedthrough was used in full height waveguide no structure was seen. It is possible that the full height configuration decouples the junction from resonances at the other side of the waveguide. It is not known if the low-frequency resonances discussed above contributed to excess noise in the presence of a LO bias. There were no strong features in β^2 which correlated with these resonances. At best they are a nuisance, since the rapid variation of R_D with dc bias makes the mixer response more sensitive to drift.

VIII. rf COUPLING

The coupling of the signal and the LO into a junction can be characterized by an observation of its effect on the static I-V curve, as is shown in the series of curves in Figs. 3, 4, and 5. According to the theory outlined in Ref. 1, there is a range over which the dc current changes linearly with the square root of LO power:

$$\frac{\partial I}{\partial (P_{LO})^{\frac{1}{2}}} = - S_1 \left[\frac{8 R_S}{(R_S + R_L + R_{rf})^2 + X^2} \right]^{\frac{1}{2}} . \tag{4}$$

Here S_1 is a decreasing function of normalized frequency which has been evaluated by various authors,[1,25] and $R_{rf} \approx \Omega^2 R$ is an effective junction impedance that is negligibly small for all of the junctions we have tested. The remaining terms R_S, R_L, and X characterize the antenna impedance seen by the junction. R_S is the resistance associated with the rf source, R_L represents lossy elements (other than the junction) in the microwave matching structure, and X is the reactive component of the impedance. It is instructive to compute the parameter

$$Z_x \equiv - 8 S_1^2 \Bigg/ \frac{\partial I}{\partial (P_{LO})^{\frac{1}{2}}} \tag{5}$$

for the junctions we operated as mixers. Provided the term R_{rf} can be neglected, Eq. (4) implies that if the response of a junction obeys the prediction of the RSJ model, Z_x can only depend on characteristics of the mixer mount, plunger position, wire size, etc. In particular, Z_x evaluated for a series of junctions at the plunger position giving maximum response should be constant. In Table I the minimum values of Z_x obtained in two mixer mounts (full height and reduced height guide) are given. The results are reasonably consistent for the full-height mount, considering the range of junction parameters involved. There is not enough data for the reduced height mixer to be statistically significant. A good idea of the consistency of the predictions from the RSJ model can be obtained by considering a sequence of junctions from Table I with the same resistance. In this case the external impedance remained fixed (all that varied was the junction temperature) so that any variations in Z_x reflect deviations from the predicted dependence of junction response on normalized frequency. In some cases there is a range of a factor 2 in response.

We have calculated the value of Z_x using microwave circuit theory. The terms in (4) are given by

$$R_S = \frac{Z_o}{4}\left(1 + \Gamma^2 - 2\,\Gamma\cos 2\theta\right)$$

$$R_L = \frac{Z_o}{4}\left(1 - \Gamma^2\right) \qquad (6)$$

$$X = \frac{Z_o}{2}\,\Gamma\sin 2\theta + X_w\,,$$

if the guide is matched to the source in one direction and terminated in the other direction by a short of reflection coefficient Γ, at a plane θ electrical degrees from the junction.

In arriving at Eqs. (6) we have used several simplifying assumptions: (1) The diameter of the wire is small compared to the waveguide width. (2) The wire sees an effective short circuit at the waveguide wall opposite the junction. A properly designed IF filter should realize this condition. (3) The predominant loss in the matching circuit is the leakage past the tuning plunger, which leads to a value of $\Gamma < 1$.

In reduced height waveguide ($b << \lambda/4$) the scaling impedance Z_o is the "wave impedance" $377(\lambda_g/\lambda)(2b/a)$ ohms, using standard notation.[26] An analytical expression for the inductance X_w of the contacting wire also exists for the reduced height limit,[26] which gives $X_w \approx Z_o = 150$ ohms for our mixer using 50 μm wire. A value $\Gamma = 0.9$ was inferred for the plunger by observing the Q of a cavity that was formed between a non-contacting wire and the plunger. This is about what would be expected from the clearances involved. Inserting the above values into (6), we find using (4) and (5) that the minimum Z_x in the reduced height mixer is expected to be $\sim$ 180 ohms, at $\theta = 132°$. In Table I we see that one of the junctions actually had a value of Z_x less than 180 ohms - i.e., had a larger response to rf power than predicted by the RSJ model. There are not enough data to draw conclusions about the magnitude of the response of a "typical" junction in the reduced height mixer, but we can conclude that at least some junctions respond as expected from the model.

As a further check on the parameters of the reduced height mixer mount, we compared the <u>relative</u> junction response as the plunger position was varied to that expected from Eqs. (4) and (6). The response of the two junctions listed in Table I could be well fit using $\Gamma = 0.9$ and $X_w/Z_o = 1.0$ and 1.5, respectively. Note that this determination makes no assumption about the detection mechanism in the point, as long as the junction resistance is sufficiently small. This condition was best met by the first junction, which tends to corroborate the parameters used in estimating Z_x.

While we have much more data for the full-height mixer, it is difficult to predict Z_x from microwave circuit theory. Existing treatments[27,28] are somewhat contradictory, but do agree in the prediction that Z_o and X_w will be strong functions of waveguide height b when $b \gtrsim \lambda/4$. It is therefore not very meaningful to compare our observed values of Z_x to some "theoretical" value. We note, however, that the usual supposition that reduced height waveguide is necessary for matching to low impedance devices is not necessarily true.

IX. CONVERSION EFFICIENCY

We define conversion efficiency as the ratio of available power at the difference (IF) frequency to the available signal power at the mixer input. The I-V curve measurements that are involved in determining Z_x can also be used to compute the conversion efficiency in the limit of low IF frequencies:

$$\eta = \left(\frac{\partial I}{\partial P_{LO}^{1/2}}\right)_\nu^2 \frac{R_D}{8} = S_1^2 \frac{R_D}{Z_x} \quad . \tag{7}$$

From RSJ model simulations[1] it is expected that Eq. (7) should remain valid for IF frequencies as high as $\nu_{LO}/10$.

Our apparatus permits a "hot/cold" test of conversion efficiency in the range of IF frequencies used in our noise measurements (usually $\sim$ 50 MHz). The technique is to observe a change in T_{out} (defined in section IV) when the temperature T_s of a blackbody source coupled to the mixer is changed. Then we have

$$\eta = \frac{1}{2A} \frac{\Delta T_{out}}{\Delta T_s} \tag{8}$$

where A is the attenuation between the source and the input to the mixer, and the factor 2 arises because two noise sidebands from the source are down-converted into the IF bandwidth. The source temperatures used in our tests are room temperature (297 K) and liquid nitrogen (77 K). When the mixer is connected directly to the output of the directional coupler, we have (see section II) A = 0.70. We then determine T_{out} from a measurement of the IF power as outlined in section IV. Note that as defined in Eq. (8) the conversion efficiency involves the available, rather than delivered, IF power.

An important practical problem that is encountered in measurements of this sort arises from a saturation mechanism described in Ref. 1. When the source is coupled over a wide bandwidth, modulation of T_s can have an effect on R_D. This is a version of the well-known "noise rounding" phenomenon. This modulation translates into a variation in T_{out} which is not related to linear mixing. When there is good coupling to the IF amplifier the sign of this effect is to reduce T_{out} as T_s increases - i.e., to make η appear too small or even negative. We have observed very large "anomalous" dependences of T_{out} on T_s, especially near regions in an I-V curve where R_D is large. These regions are found to show a strong dependence of differential resistance on T_s.

The modulation in R_D is essentially a square-law detection phenomenon, with contributions from a wide range of frequencies from the source. To avoid such an effect the bandwidth over which the source is coupled to the junction must be reduced. We constructed a band-pass filter consisting of a pair of thin brass sheets with 0.84 mm irises separated by $\approx \lambda g/2$ in the F-band waveguide. It had a Q of 20 and a loss at the center frequency (130 GHz) of 1.4 ± 0.3 dB. While these values were determined at room temperature, there is no reason to think that they would be different at 4.2 K.

When the filter was inserted, the modulation of R_D by the source temperature was greatly reduced, and in most cases could not be resolved with sensitive lock-in techniques. To be absolutely sure that no such effects were occuring we constructed an additional attenuator from Eccosorb MF-110 to be inserted ahead of the mixer. Its attenuation at 4.2 K was measured to be 5.0 dB. When the attenuator alone was used, substantial modulation effects could still be observed. However with the combination of band-pass filter and 5.0 dB attenuator such effects were completely absent. We could then assume with confidence that any change in IF power resulting from a change in source temperature is the result of linear down-conversion. It is expected that the experimental conversion efficiencies obtained by the "dc" method (Eq. (7)) and the hot-cold method (Eq. (8)) should agree, providing that: (1) The conversion efficiency is independent of the IF frequency at least up to the range of frequencies over which the IF system is coupled. This is certainly expected from any mixing model involving the Josephson effects. (2) The contribution from harmonic mixing is negligible in the hot-cold test. It is likely that the coupling at harmonic frequencies is much worse than near the fundamental (LO) frequency. Even if the coupling were the same, the largest excess in T_{out} would be $\sim$ 30% according to the RSJ model.[1] If the above criteria are assumed to have been met, we can regard any discrepancy in the two determinations of η as a check on the calibration of LO power described in section II, and the attenuation A in the signal line. On the average, the hot-cold values for η exceeded the "dc" values by $\sim$ 35%. This is not unreasonable in view of the uncertainty in the original calibration and the possibility of long-term changes.

Note that the conversion efficiencies discussed above are referred to the output of the directional coupler. To determine the efficiency of the mixer itself the attenuation of the cold attenuator and the band-pass filter must be known. We estimate the uncertainty in these numbers to be ± 10%.

The measured conversion efficiencies for a number of junctions are listed in Table I. Several had values $\eta \sim 0.3$, which is about the best that can be achieved in Schottky diode mixers.[29] Most of the values quoted were obtained by the "dc" method, since the hot/cold method gave precise values only for the best junctions.

X. MIXER PERFORMANCE

In addition to conversion efficiency, the single side-band mixer noise temperature T_m provides an important measure of mixer performance in the context of low noise receivers.

$$T_m = T_{out}/\eta = T\beta^2 R_D/(R\eta) \ . \tag{9}$$

Combining Eqs. (2) and (7) yields

$$T_m = T\left(\frac{\beta^2}{S_1^2}\right)\left(\frac{Z_x}{R}\right) \ , \tag{10}$$

where, according to the RSJ model, the second term is a weak function of normalized frequency in the range $0.1 < \Omega < 0.9$. This approximation breaks down when Z_x is comparable to R, a condition that was rarely achieved in our experiments.

In Table I we summarize the relevant parameters for a number of junctions which illustrate the range of behavior observed. All of them were of the high P_o type. Note particularly that the results for η and T_m are referred to the <u>input</u> of the mixer.

The best results we have seen (T_m = 180 K, η = 0.30) compare very favorably with the best reported for a cooled Schottky diode at a somewhat lower frequency (T_m = 300 K, η = 0.26 at 115 GHz).[29]

To put these results in perspective, it is useful to estimate the overall performance of our system as a radiometer. The figure of merit most often used in this case is the single side-band receiver noise temperature:

$$T_R = [(T_m + 2T') + T_{IF}/\eta]/A . \qquad (11)$$

Here A is the attenuation between the system input (the K-band port at the top of the cryostat, in our case) and the mixer. Without the cold attenuator we would have A = 0.51, including the 1.4 dB loss in the band-pass filter. In Eq. (11), T' is the re-radiated power in the signal and LO lines, referred to the mixer input. From the estimates in section II we find $T' \simeq 31$ K. The IF amplifier noise temperature T_{IF} should be referred to the mixer output - i.e., mismatch and attenuation effects are assumed to be incorporated in T_{IF}. Supposing that a recently reported[30] cooled FET amplifier with $T_{IF} = 30$ K were used with our best mixer, we would have a single side-band receiver noise temperature $T_R = 670$ K.

XI. CONCLUSIONS

We have found that point contact Josephson junctions made according to the right prescription show reasonable agreement with the predictions of the RSJ model when operated as mixers at 130 GHz. The output noise can be less than 1.5 times the predicted value, and typically is in excess by a factor 2 when the coupling is optimized. The conversion efficiency of some junctions was a little better than suggested by the model, but agreed with the model calculations to within the accuracy with which the microwave circuit could be characterized. Our best results were a conversion efficiency of 0.30 and a mixer noise temperature of 180 K (both ± 20%). These constitute a significant improvement over the best performance using Schottky diodes at comparable frequencies.

Most of the junctions we studied satisfied the condition $R \ll Z_x$. The experimental values of T_m were usually within a factor 2 of the RSJ model prediction in this limit, $T_m \approx 10\ T\ Z_x/R$. The model suggests that both the conversion efficiency and output noise will increase for smaller values of Z_x/R, so that only modest improvements in T_m will result. Since the simulated results depended in a complicated way on system parameters, it is difficult to make numerical estimates of the limiting performance expected. We were unable to explore the interesting regime $Z_x/R \lesssim 1$ with the microwave mount that was used. (Had it been possible to make good junctions from 0.3 mm wire, a 3-fold reduction in Z_x would have been possible in our design.)

At a lower frequency,[5] considerable improvement in T_m resulted from cooling the junction below 4.2 K. With the junction fabrication techniques we used, the junctions usually became hysteretic at temperatures much below 4.2 K. However, simulations of the quantum limit $h\nu_{LO} \gg 2kT$ show that no improvement can be expected at temperatures below $h\nu_{LO}/2k = 3.1$ K at 130 GHz.

The junctions we used had RI_c products which were less than half the theoretical limit. Nb point contacts with values close to the upper limit have been made.[11] The simulator results show that a higher RI_c (lower Ω) would give a larger conversion efficiency but would not have much effect on the noise temperature. Therefore, we expect that improved junction parameters should be most important at frequencies above 130 GHz.

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Table I. The important parameters for a representative group of junctions used as mixers. All junctions were made with 50 μm Nb wire against a Nb flat, and were of the high P_o type. Junctions with the same value of R differed only in their operating temperature. The first five were mounted in a reduced height mixer, and the rest were in a full height mount. In some cases the data were taken with a non-optimal plunger position. In these cases an appropriate correction was applied to Z_x. Starred values of η and T_m were obtained via the hot/cold source technique. In the remaining cases η and T_m were inferred from measurements of β^2 and the LO coupling. Missing values for β^2 imply anomalous behavior for that junction. Assumed system losses were: bandpass filter, 1.4 dB; cold attenuator, 5.0 dB; signal line, 1.55 dB. Note that the radiated power from the walls of the signal and LO lines is included in T_m. A rough estimate for this contribution is $\sim$ 20 K.

Table I

	R	R_D	Ω	T	Z_x	β^2	η	T_m
1	11.6	19	.24	3.3	130	11.3	.091	670
2	11.6	14.5	.29	4.2	180	6.8	.056	645
3	11.6	17.1	.47	6.35	253	-	.036	-
4	59	148	.25	4.2	280	26	.34	800
5	59	100	.39	5.65	205	9.9	.26	365
6	8.5	27	.49	4.2	170	7.6	.082	1230
7	8.5	20.1	.80	6.0	135	-	.039	-
8	39	82	.40	4.2	180	34	.27	1100
9	39	58	.58	6.0	170	6.5	.15	390
10	50	76	.38	4.2	160	10.8	.29*	225*
11	50	56	.60	6.0	185	5.0	.13	265
12	78	56	.30	4.2	115	18	.30*	180*
13	84	55	.40	6.25	115	11.9	.25*	200*
14	84	67	.71	7.45	225	7.5	.096	460
15	185	85	.41	4.2	135	33	.30*	215*

Figure Captions

Fig. 1. Schematic diagram of the microwave circuit and the cryostat design. Components are standard, exccpt as noted: A - brass circular waveguide, 2.46 mm ID; B - brass K-band waveguide; C - transition to WR-8 (1 × 2 mm) waveguide; D - 5.0 dB attenuator; E - bandpass filter, Q ∿ 20, loss ∿ 1.4 dB; F - solid jacketed stainless steel coax, 0.141" OD.

Fig. 2. Cross section of one mixer mount used. The waveguide dimensions are 1 × 2 mm, except in the reduced height section where the height is 1/3 mm. The transition to full height on the plunger side occurs over a nominal distance of 1.25 guide wavelengths. The length of the low impedance coaxial section is 0.30 mm.

Fig. 3. Current-voltage characteristics of a high-P_o Nb-Nb junction at 5.8 K. The uppermost curve is without LO, and those beneath are for progressively increasing LO levels. When heated above its transition temperature the junction resistance was 29 ohms, implying $\Omega_{LO} = 0.31$. The strong feature at 0.8 mV occurs only for very small LO power, and is attributed to a resonance in the impedance seen by the junction at ∿ 390 GHz.

Fig. 4. Current-voltage characteristics of a junction similar to that of Fig. 3, except with a larger normal resistance (70 ohms). The normalized frequency is $\Omega_{LO} = 0.15$, at T = 5.55 K.

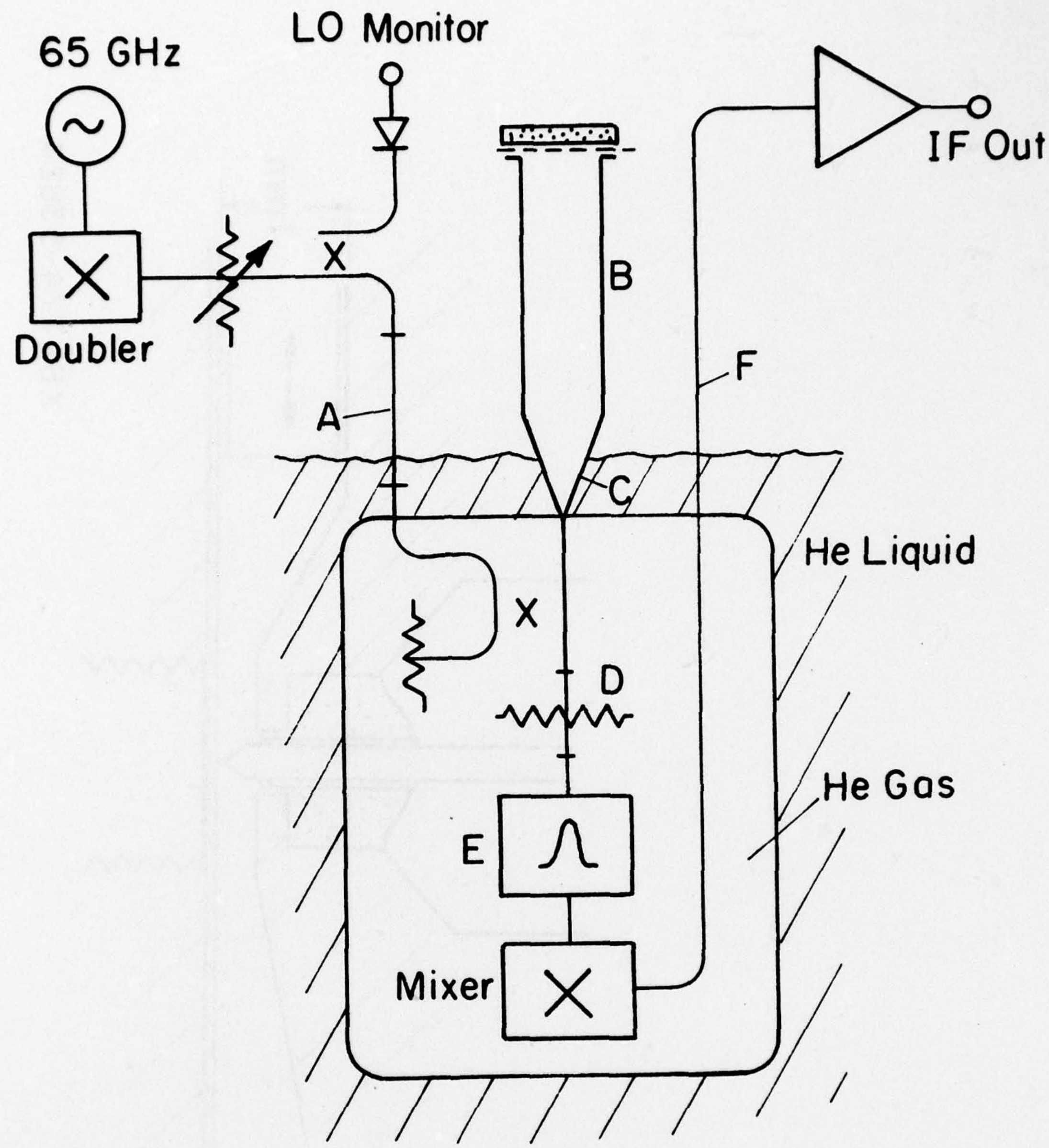
Fig. 5. Current-voltage characteristics of a junction identified as heating dominated (low P_o). The uppermost curve is without LO, and the lowest is with maximum LO applied. The point was Nb-Zr alloy, and the flat was pure Nb.

Fig. 6. The dependence of the output noise parameter (dashed line) on bias for the junction shown in Fig. 3, along with the corresponding current-voltage characteristic. The LO power was set at a level appropriate for operation as a mixer. The coupling was intentionally reduced to avoid effects of the external circuit on the noise.

Fig. 7. The minimum noise parameter between the zero'th and first steps for a number of junctions, as a function of their normalized frequency Ω_{LO}. The rf coupling was intentionally reduced to avoid effects of the external circuit on the noise. A distinction is made between junctions with $R > 60$ ohms (open circles) and $R < 60$ ohms (solid circles). All junctions were made of Nb and were of the high-P_o type. The line shows the result of simulations based on the RSJ model (Ref. 1).

Fig. 8. A plot similar to that of Fig. 7, except that the LO coupling to the junctions was optimized. A distinction is again made between junctions with high resistance (open triangles, $R > 60$ ohms) and low resistance (solid triangles). The dots represent the best of a number of low-P_o junctions. A rough estimate of the excess noise contributed by connection to a low-impedance external circuit can be made. The noise that would be measured in the absence of this effect is indicated by an arrow in those cases where the contribution exceeds $\sim 25\%$.

Fig. 9. (dashed curve) The dependence of the noise parameter on bias voltage for the junction of Fig. 3 without LO bias (dashed curve) along with the corresponding I-V curve (solid curve). The RSJ model prediction for this case (Ref. 23) is also shown (chain curve).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IF Out
X
Doubler
B
A
F
C
He Liquid
X
D
He Gas
E
Mixer
XBL774-5383

Fig. 1

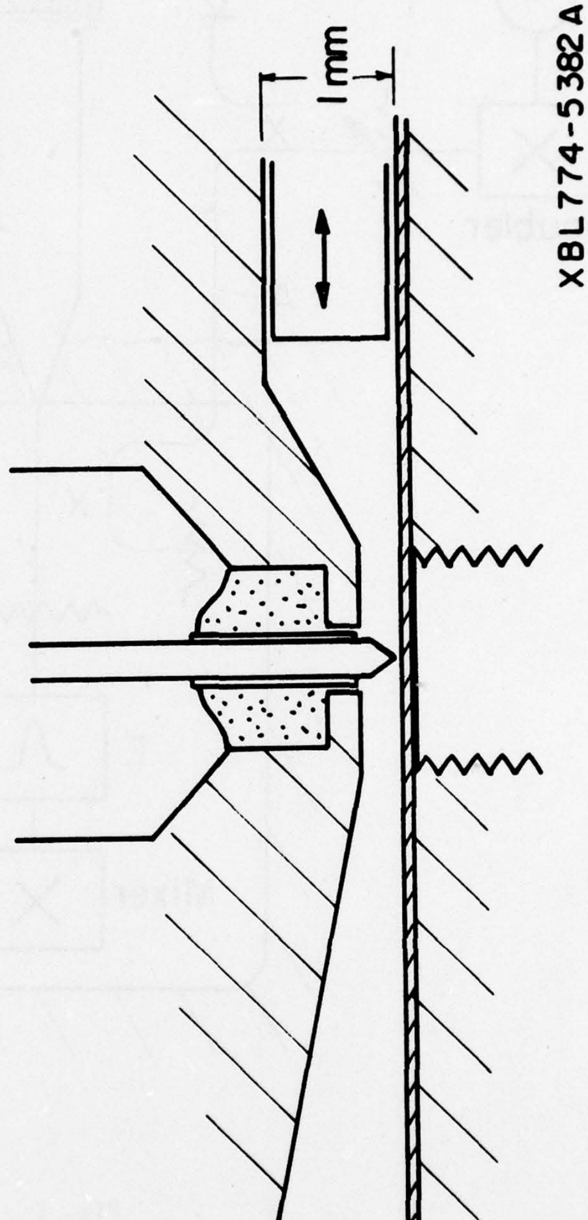


Fig. 2

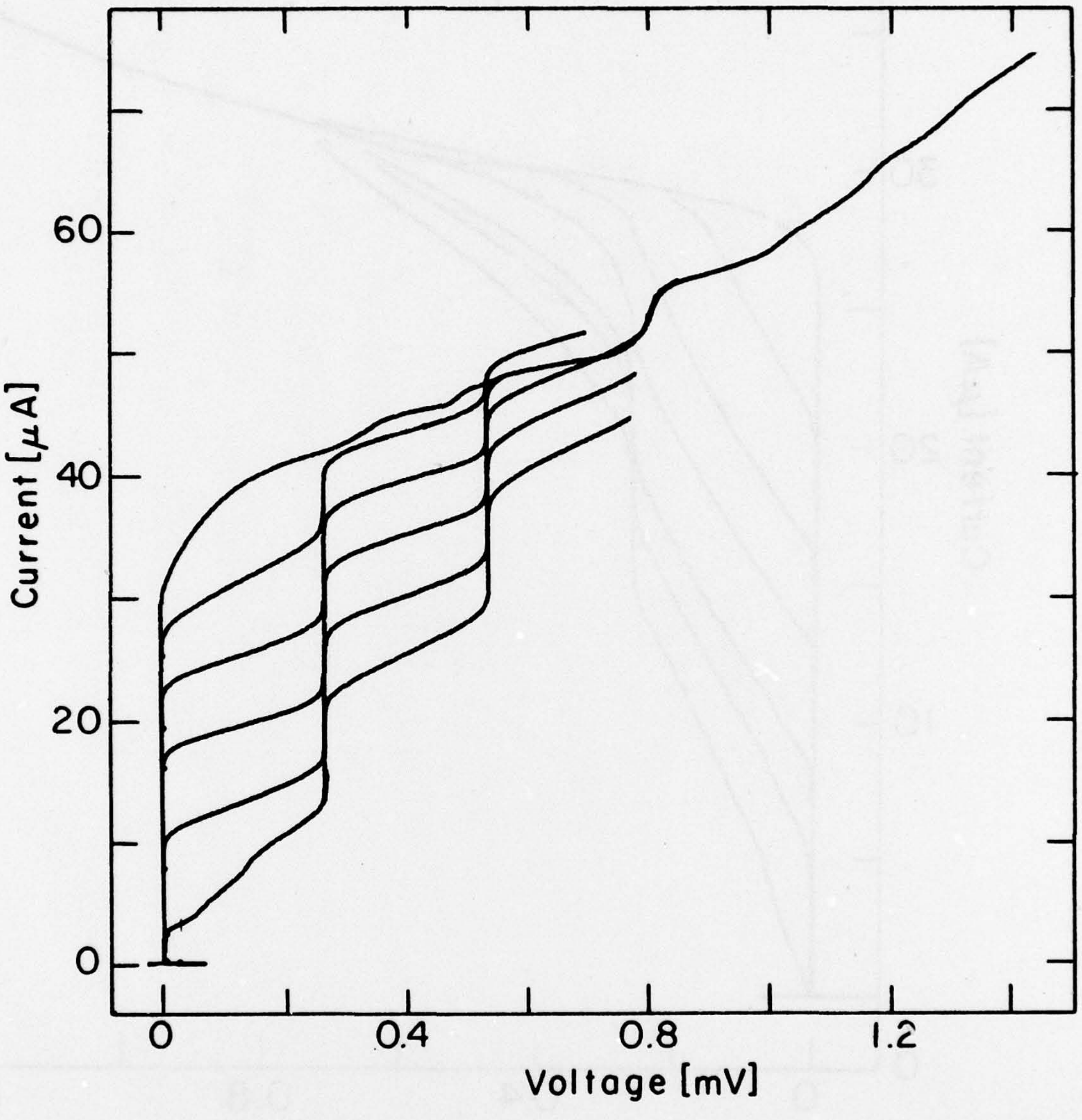


Fig. 3

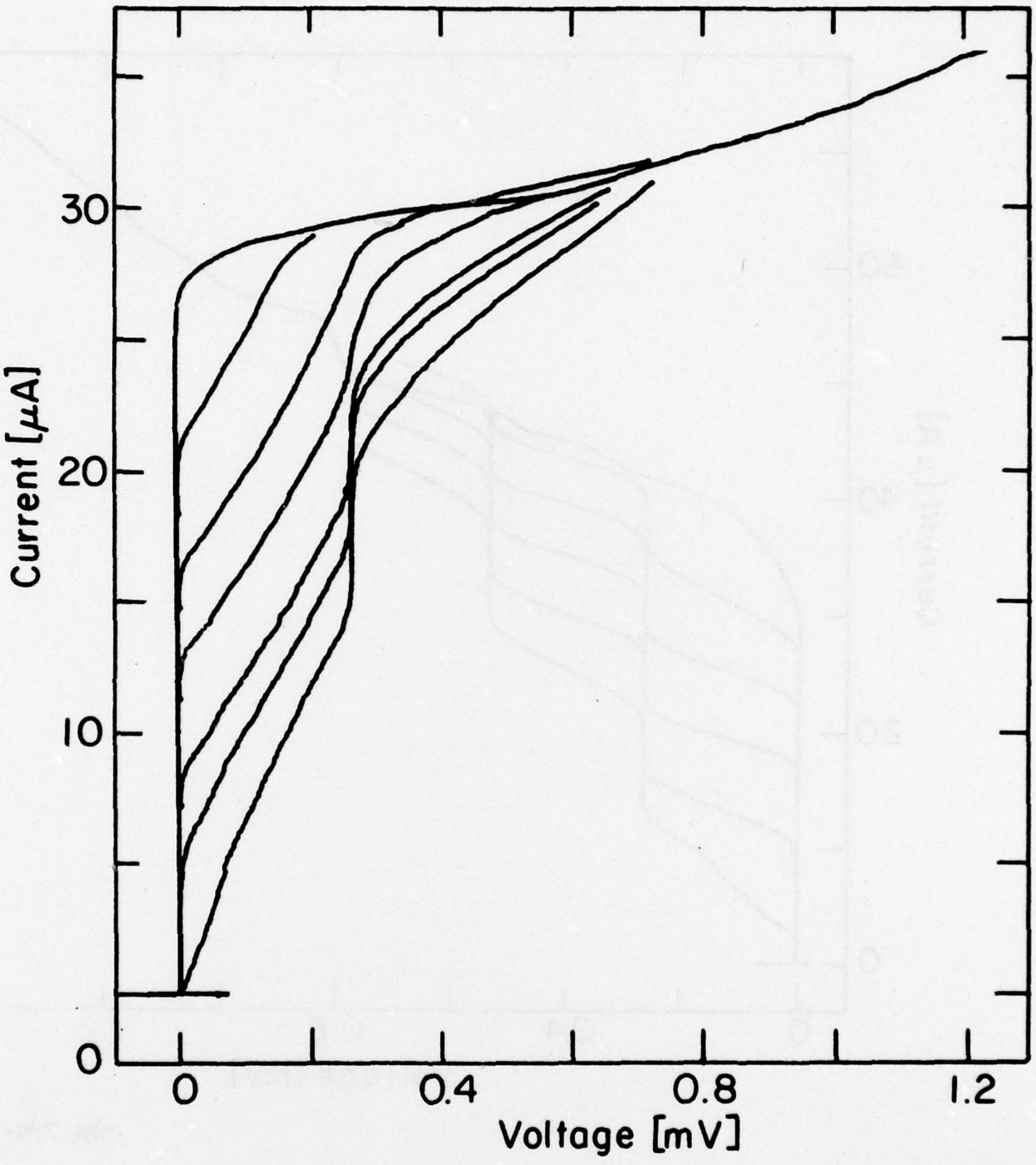
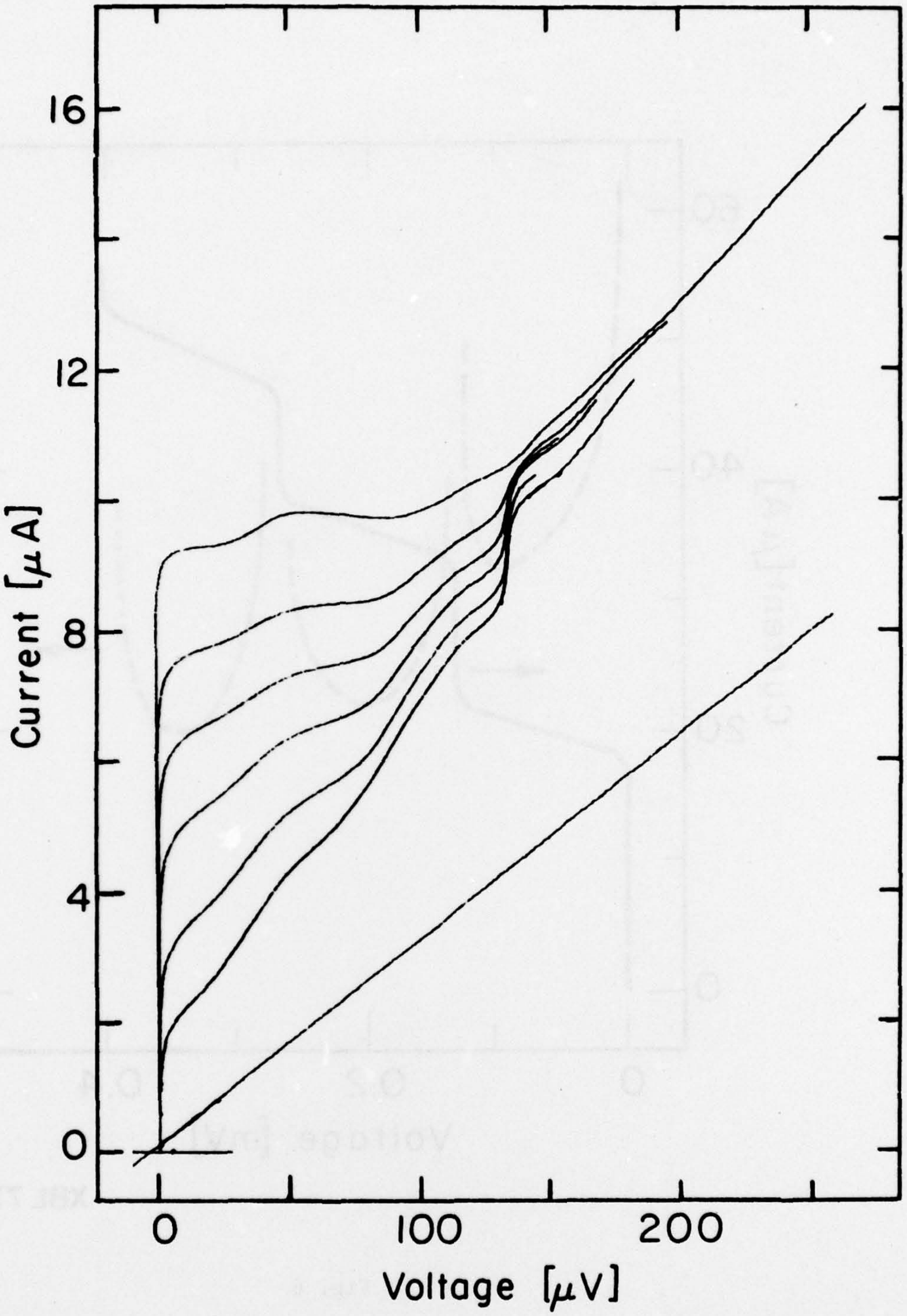
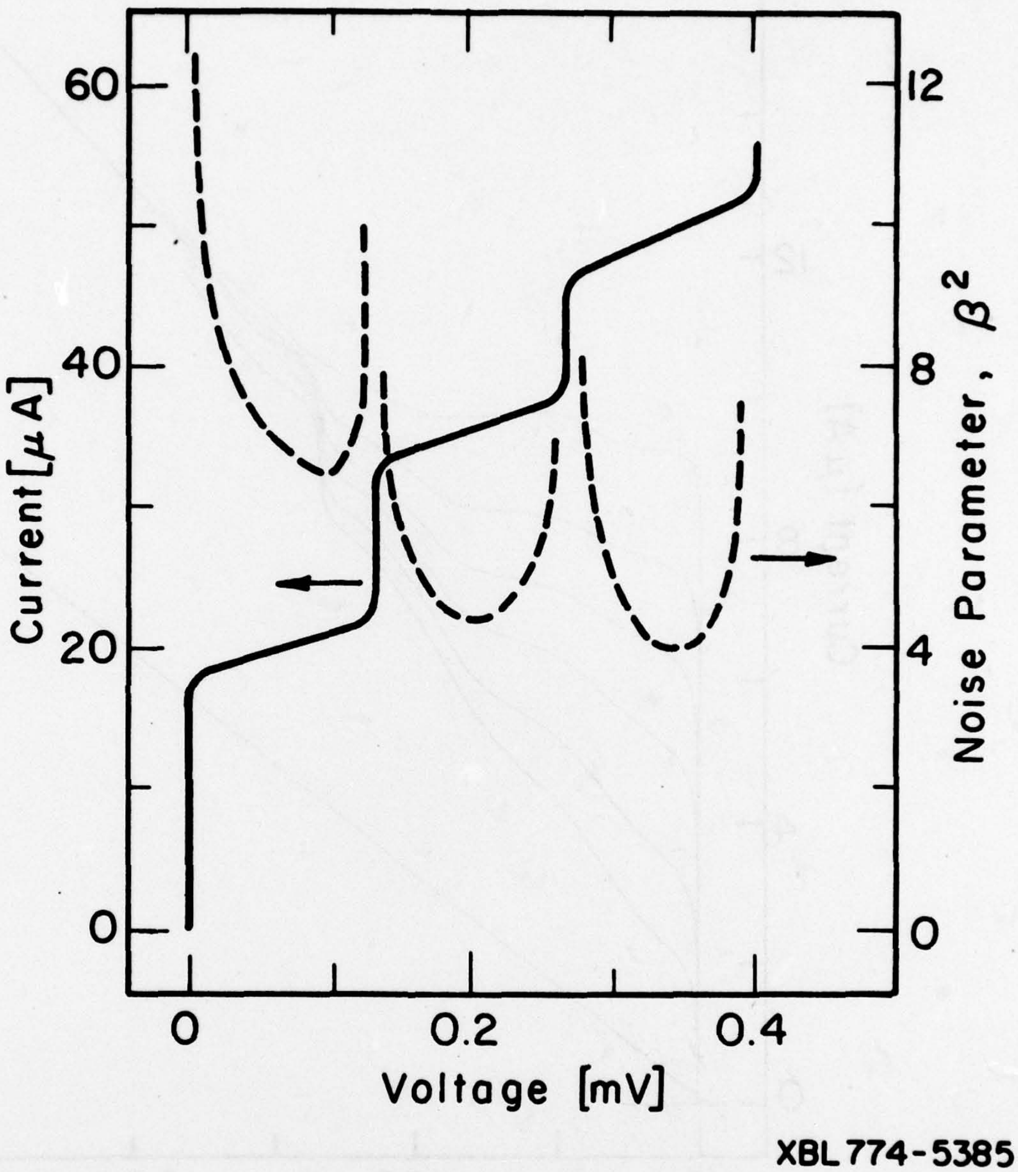


Fig. 4



XBL 774-5377

Fig. 5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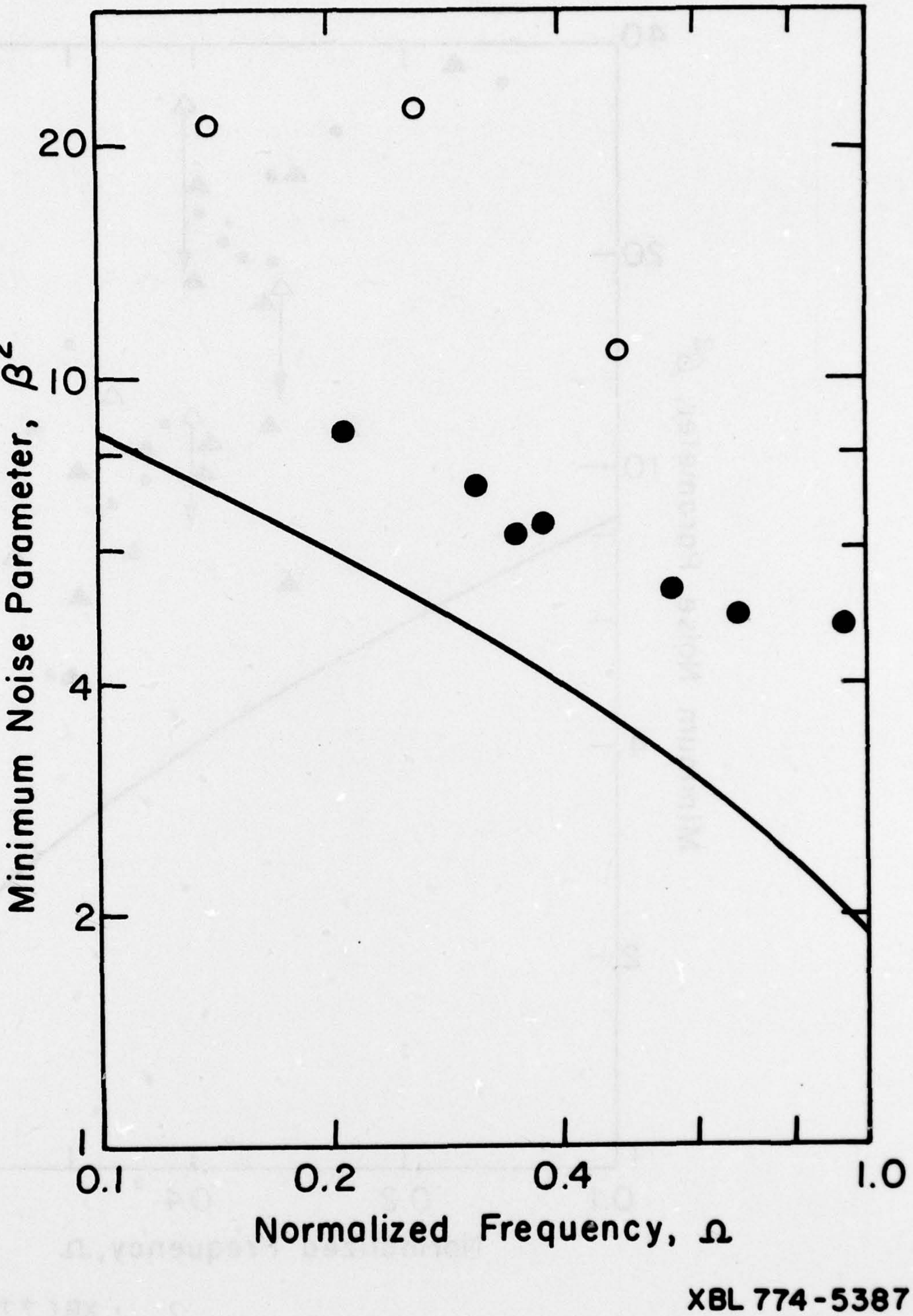
40
20
0
12
8
4
0
0
0.2
0.4
Voltage [mV]
Current [μA]
Noise Parameter, β²
XBL 774-5385

Fig. 6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10
4
2
1
0.1
0.2
0.4
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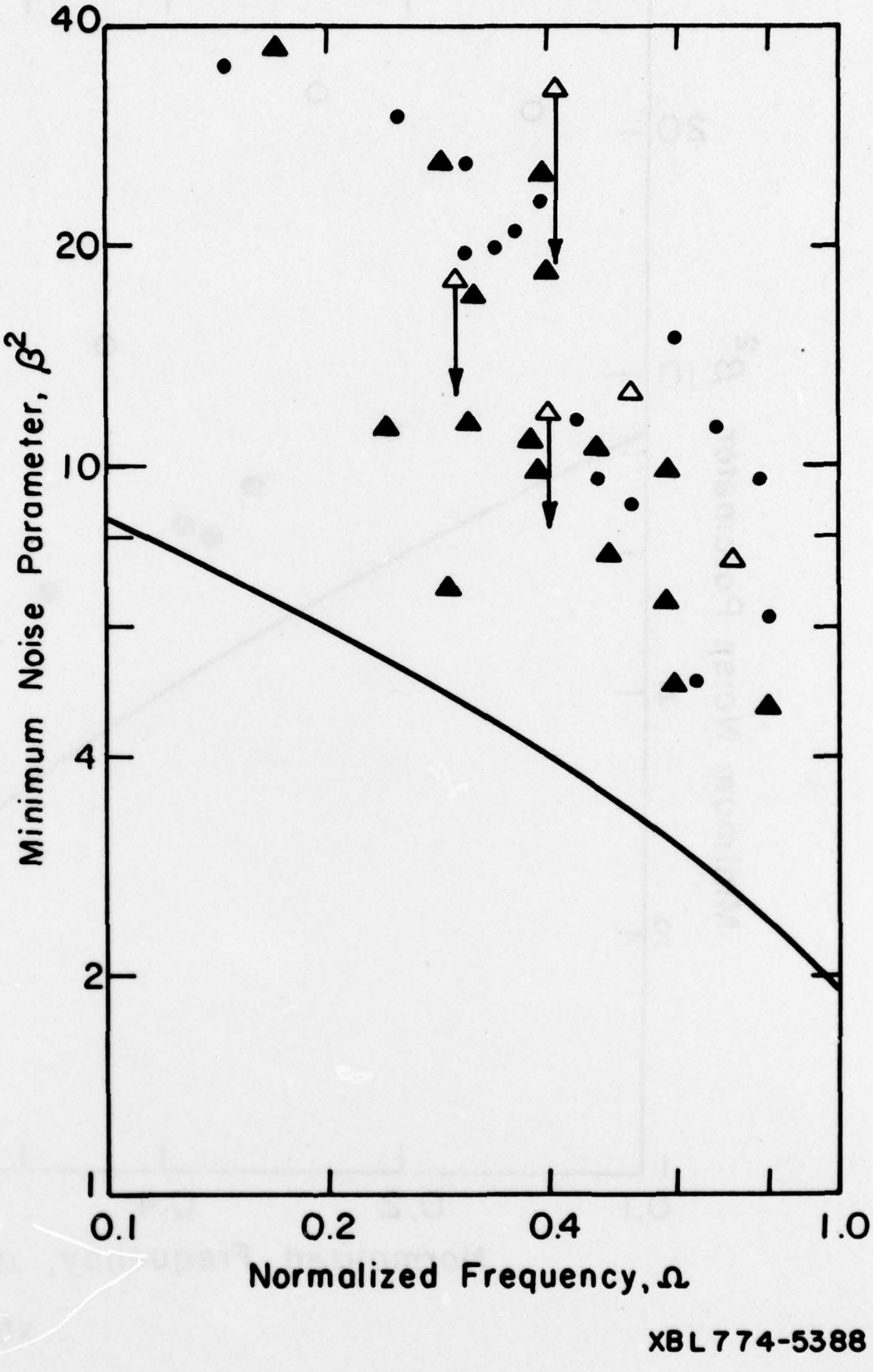
Minimum Noise Parameter, β^2
Normalized Frequency, Ω
XBL 774-5387

Fig. 7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20
10
4
2
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Minimum Noise Parameter, β^2
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1.0
Normalized Frequency, Ω
XBL774-5388

Fig. 8

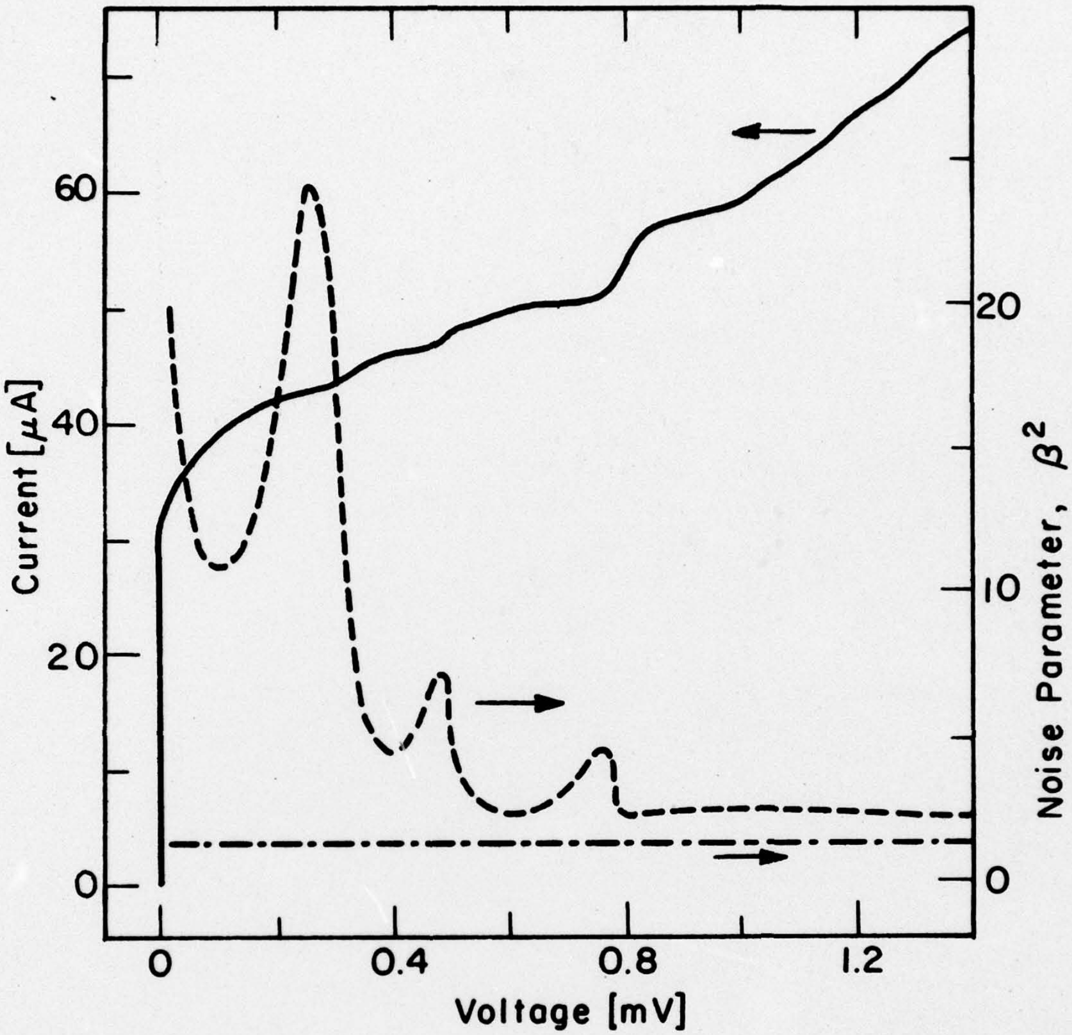

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Fig. 9